A Potentially Useful Role for Airborne Separation in 4D-Trajectory ATM Operations

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An aircraft equipped with Airborne Separation Assistance System functions and 4-dimensional trajectory management capabilities can have significant, potentially transforming, value to Air Traffic Management at the local and system levels. This paper discusses how certain vital characteristics envisioned in the Next Generation Air Transportation System enable some Air Traffic Management functions to be distributed to properly equipped aircraft, and it defines and illustrates this equipage level in a potential application. The new equipage level, perhaps the most capable of many levels permitted, enables an effective implementation of both near- and long-term 4-dimensional trajectory operations in complex airspace, with the aircraft providing the near-term tactical functions and conforming to the long-term trajectory attributes coordinated with ground-based Traffic Flow Management authorities. NASA's recent research and development of this proposed aircraft equipage for en-route and terminal-arrival operations is summarized. The role the equipage level may play in addressing key implementation challenges of reducing ground infrastructure cost, building in security and safety, and scaling to traffic demand is discussed.

Nomenclature

4D	=	Four Dimensional
4DT	=	Four Dimensional Trajectory
ADS-B	=	Automatic Dependent Surveillance Broadcast
AFM	=	Autonomous Flight Management
AMSTAR	=	Airborne Merging and Spacing for Terminal Arrivals
AOP	=	Autonomous Operations Planner
APS	=	Airborne Precision Spacing
ASAS	=	Airborne Separation Assistance System
ATM	=	Air Traffic Management
CAASD	=	Center for Advanced Aviation System Development
CAVS	=	CDTI Assisted Visual Separation
CDTI	=	Cockpit Display of Traffic Information
DAG-TM	=	Distributed Air-Ground Traffic Management
FMS	=	Flight Management System
JPDO	=	Joint Planning and Development Office
MFF	=	Mediterranean Free Flight
NAS	=	National Airspace System
NGATS	=	Next Generation Air Transportation System
R&D	=	Research and Development
RNAV	=	Area Navigation
RNP	=	Required Navigation Performance
RTA	=	Required Time of Arrival
TFM	=	Traffic Flow Management

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I.   Introduction

R EVITALIZED demand for air transportation is causing many commercial and government organizations to take a new, hard look at the capabilities of the current air transportation system with the objective of determining what changes are necessary to accommodate the anticipated future demand. As a result of studies conducted by such organizations as the National Research Council[1] and the Commission on the Future of the United States Aerospace Industry,[2] which conclude that the current system cannot scale to meet future need, the U.S. Congress has called for a national plan that will transform the nation's air transportation system to meet the needs of the year 2025 while providing substantial near-term benefits. The Joint Planning and Development Office (JPDO) was established for this purpose, and it is currently working to define the framework of the Next Generation Air Transportation System (NGATS).[3]

The JPDO vision for Air Traffic Management (ATM), while still under development and subject to change, indicates a future system that may look quite different than today's system.[4] Three examples of transformation to be discussed below are "net-enable" information access, performance-based services, and aircraft trajectory-based operations. These three examples provide the basis for aircraft to adopt a new role as an active ATM resource.

Net-Enabled Information Access
A substantial increase in information availability is expected to be a dominating factor in promoting greater shared awareness of system operations across many time scales, enabling a redistribution of functions and responsibilities among the key players. Large quantities of data will be pushed and pulled throughout the system in a real-time, free-flowing, broadband-network environment. A natural conclusion of this envisioned architecture is that any system participant (e.g. air traffic controller, flight crew, dispatcher) deemed best suited for a particular function will not be impeded from performing that function by a lack of timely and accurate information. Although the feasibility of developing such a high-bandwidth information system at reasonable cost and reliability has yet to be established, the notion is compelling that information newly available in a given place creates the opportunity for new functions to be performed in that place. The resulting challenge, therefore, is to decompose ATM into a set of distributable functions, to determine which functions are best performed by whom, and to determine what information is needed at that location to perform each function. Although not all ATM functions are appropriate for distribution, the desire to eliminate workload bottlenecks inherent in the current system requires that some level of functional distribution be explored.

Perhaps no better harbinger of ATM transformation exists than the advent of the airborne-distributed surveillance system. JPDO is exploring the possibility of requiring every aircraft to participate at some level in distributed surveillance. The applicable emerging technology is Automatic Dependent Surveillance Broadcast (ADS-B), and it may have three notable impacts on the nature and use of air traffic surveillance. First is a change in the source of aircraft position data from ground-based sensors (e.g. radar) to aircraft-based sensors (e.g. Global Navigation Satellite System receivers). Of the many distinctions here, perhaps the most relevant to ATM is that the aircraft position and its data accuracy that are broadcast to the receiving audience will be the same as those known to the onboard navigation systems. Such shared awareness of position can yield a measurable reduction in surveillance uncertainty and corresponding improvements in efficient use of airspace through reduced traffic separation standards. A second notable impact of airborne broadcast surveillance is the ability to include intent information in the messages. With this new information, the receiving audience can know in real time where each aircraft is intending to fly and any changes to that plan as they occur. The intent message may contain, for example, a sequence of planned 4-dimensional (4D) waypoints consisting of latitude, longitude, altitude, and crossing time. Again, since the data source for this information is the aircraft's navigation system, the opportunity exists for nearly complete consistency between the sender and receiver's prediction of future position for that aircraft. A third impact, more aptly described as a novel ATM opportunity, is the ability for aircraft systems to actually be a receiver of the surveillance data and to make use of it in some way that benefits ATM. Although increasing flight crew awareness of local traffic is an obvious initial safety benefit, the real ATM benefit relates back to the first discussion on net-enabled information access – that having this surveillance data on the flight deck opens up the possibility that certain traffic-related maneuver decisions could now be moved onboard. The technology that can be installed on aircraft to support traffic-related ATM functions is termed "Airborne Separation Assistance Systems" (ASAS), and international principles of operation using ASAS have been defined[5] and are being pursued through new proposed applications, as will be discussed in Section II.

Performance-Based Services

As a second example of how the future ATM system may differ from the current system, the JPDO is giving consideration to the notion of performance-based services and operations. In the current JPDO model, the NGATS will dynamically conform to a "required total system performance," in which National Airspace System (NAS) resources (e.g. runways) are managed according to real-time demand, and the performance capability of aircraft may determine their ability to access those resources. A conclusion from this is that aircraft operators may be permitted to equip along a spectrum of performance levels, as determined by their need for access to high-demand resources, such as airspace near a major airport during peak-use periods. A resulting design challenge, therefore, is to define various levels of equipage and capability that support ATM requirements at different levels of resource demand. The third transformation area of aircraft trajectory-based operations provides the context in which to define these levels that best supports ATM.

Aircraft Trajectory-Based Operations

For the more complex airspace environments, JPDO is currently exploring how "4D Trajectory" (4DT) operations might be applied. Although the precise implementation of 4DT operations is yet to be determined, the basic idea likely includes requiring each aircraft to precisely follow a custom-made 4DT consisting of a specified path and an along-path time conformance requirement. This 4DT will have been determined to assure adequate separation from traffic aircraft for the near future and to conform to a strategic Traffic Flow Management (TFM) plan that optimizes use of limited NAS resources. The performance-based equipage requirement may be that, in order to fly in airspace where 4DT operations are considered necessary, an aircraft would need to equip to receive and precisely follow a 4DT. Alternatively, other airspace in lower demand, which might for example be the same airspace at off-peak periods, might not require such equipage. As a result, multiple equipage levels can exist, but full access may be reserved for those aircraft with the highest levels of ATM-related capability. Aircraft capabilities for 4DT operations will likely include navigation systems that can follow area navigation (RNAV) procedures using an auto-flight system, can conform to high Required Navigation Performance (RNP) criteria, and can meet a Required Time of Arrival (RTA) at pre-specified waypoints. A communications and avionics architecture enabling trajectory uplink and auto-load may also be required. RNAV, RNP, and RTA are each highly relevant airborne capabilities to ATM. RNAV capability permits great flexibility in the defining of flight paths. RNP capability ensures that aircraft adherence to these flight paths is well known. RTA capability allows aircraft to precisely conform to en-route or arrival schedules. Using these capabilities together, an aircraft's complete flight can be prescribed and precisely followed.

So how do these three examples of NGATS transformation (i.e. net-enabled information access, performance-based services, and aircraft trajectory-based operations) provide aircraft with a potential new opportunity and role as a valued ATM resource? The first example showed that vastly improved information flow will enable the redistribution of ATM functions to the best suited party (possibly different than today). In addition, it showed that the airborne equipage for receiving and processing surveillance data for nearby traffic (i.e. ASAS) will enable aircraft to define maneuvers no longer just relative to fixed waypoints but also relative to other aircraft, a function central to ATM. The second example showed that, in the vision currently expressed by JPDO, the greater the level of ATM-relevant equipage onboard an aircraft, the greater the permitted access to high-demand ATM resources. The third example illustrated the JPDO's preferred approach of 4DT management and how aircraft capability level may be linked to complex airspace access. The thesis of this paper is that integrating the airborne capabilities for 4DT operations and airborne separation result in a total capability far greater than just the former, and that the integrated capability is of such high relevance to ATM that ground systems could actually be off-loaded (with efficiencies and simplicities gained) in high-complexity airspace by delegating specific aspects of 4DT operations to the flight deck.

This paper will review several ASAS applications currently under development, define the proposed integrated capability level of "4D-ASAS" (i.e. combining 4DT and ASAS capabilities, as one of many levels to be allowed in operation), propose a model for how airborne 4D-ASAS capability can work together productively with ground-based TFM to benefit ATM, present how 4D-ASAS contributes to solving several significant ATM-related challenges faced by JPDO, and summarize recent NASA Langley development activities for this airborne capability. ATM certainly is and will remain a system-level objective, not an individual aircraft objective. This paper will illustrate that, by using 4D-ASAS capabilities, the aircraft can become a valued ATM resource in a manner that enables safe and efficient operation of a complex, high-density ATM environment.

II. Emerging ASAS Applications in Today's System

Several applications that use ASAS technology and procedures to aid the ATM system are being proposed and studied for operational implementation. This section provides a brief overview of a select few of these applications and a discussion of what lessons may be learned for promoting a significant positive impact of ASAS capability on ATM.

A. Aiding Visual Acquisition

A clear safety-related benefit of bringing ADS-B information onto the flight deck is to increase flight crew awareness of the surrounding traffic. The challenge from an ATM perspective, though, is to determine how this information can also be used to increase capacity or improve traffic flow. To promote near-term implementation potential, proposed ASAS applications generally do not involve redistributing separation responsibility. Even so, ATM improvements beyond safety are still possible. An example is the use of airborne traffic surveillance to increase the utility of visual approach operations in marginal visual conditions. The MITRE Center for Advanced Aviation System Development (CAASD) is investigating an operational concept called Cockpit Display of Traffic Information (CDTI) Aided Visual Acquisition (CAVS).[6] An excerpt from the MITRE CAASD website summarizes the objective and approach of the CAVS concept[7]:

> The purpose of CAVS is to maintain airport capacity by delaying the transition from visual approach operations to instrument approach operations as weather conditions deteriorate. The CDTI supplements out-the-window visual contact and allows the pilot to lose sight of the aircraft ahead while still keeping it "in sight" on a traffic display. By expanding the weather conditions under which visual separation may be applied, airport capacity may be maintained and delays reduced.

CAVS will enable the more flow-efficient visual procedures to be used in marginal visual conditions that currently often require reverting to instrument procedures, which are designed for safety, not throughput. In visual approach procedures, the flight crew is responsible for separation and therefore maintaining spacing behind a lead aircraft. CAVS does not change separation responsibility, but rather it extends the conditions under which visual procedures are considered suitable. As shown in Figure 1, the extension is into situations where the trailing aircraft is in visual conditions but visual contact of the lead aircraft is intermittent, for example, due to a scattered cloud deck. No doubt, CAVS will benefit ATM, but on a local, weather-dependent basis. In order to have a more pervasive impact on system-level ATM, an airborne role in spacing is needed that can be applied in all visibility conditions.
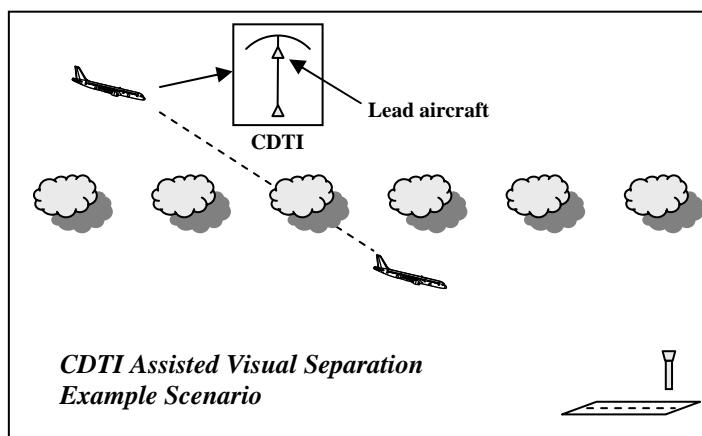

Figure 1. CAVS will enable pilots to continue visual approach procedures under conditions of marginal or intermittent visibility.

B. Sequencing & Merging

The objective of increasing capacity is often tied to controller workload, and many capacity-improving ASAS applications involve repackaging several controller tactical instructions into a single new clearance that can be executed by the flight crew using ASAS technology. An example is the Sequencing & Merging application being considered for fast-track implementation in Europe's CASCADE program. The Sequencing & Merging application has been under investigation by the Mediterranean Free Flight (MFF) Program[8] for use in en-route and arrival scenarios. Extensive research of arrival scenarios has also been performed by the Eurocontrol Experimental Center.[9] In a typical scenario, as shown in Figure 2, pilots would be instructed to merge behind an aircraft at a given distance or time and then maintain that spacing.

MFF simulations were conducted in the context of Free Route airspace (i.e. no airways or other route structure) to assess feasibility and the impact on controller workload; the studies produced mixed results. The operations proved difficult to apply due to the lack of aircraft speed flexibility at high altitude. Time frames were extended to compensate, but this led to controller interruptions during the maneuver for conflict management, which disrupted the benefits gained by the Sequencing & Merging procedure. On the other hand, researchers were able to successfully implement the procedure in the arrival domain following top-of-descent and prior to hand-off to the approach controller. The key enabling factor, beyond increased speed flexibility at lower altitudes, was the segregation of the arrival streams from departures and over-flights such that disruptions to the Sequencing & Merging procedure were eliminated. Controller workload was found to be acceptable at low traffic volumes, but unfortunately increased unacceptably as traffic demand increased.
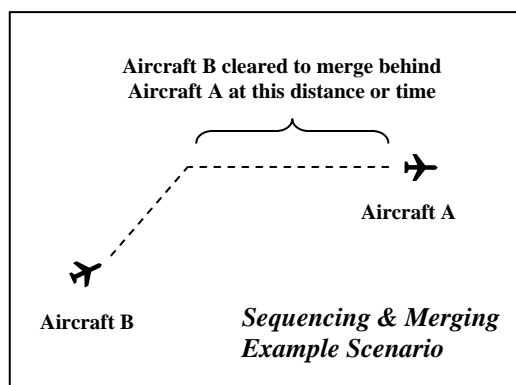

Figure 2. The Sequencing & Merging application enables controllers to assign multiple maneuvers with one clearance.

Valuable to learn here are that flexibility is an important resource in airborne ATM applications and that speed is not the most flexible degree of freedom available to an aircraft. If the speed resource is not sufficient, then other degrees of freedom must be considered. In the MFF studies, controllers solved conflicts (or segregated other traffic flows from the arrival stream) while pilots achieved the required spacing. The unstructured environment did not suit this splitting of responsibilities between pilots and controllers. Therefore, it may be necessary that, in order to pursue the benefits of airborne spacing, one of the following conditions might be necessary: (1) the airspace routing should be highly structured (e.g. RNAV routes in terminal airspace), (2) the traffic density should remain sufficiently low, or (3) local separation responsibility should reside onboard with the spacing responsibility.

Eurocontrol simulations focused primarily on arrival flight starting after the top-of-descent. In a study looking at the use of spacing instructions by controllers to establish the arrival sequence and spacing in high-demand traffic flows, controller feedback of the procedure was positive. They reported ease of use of the new procedure and a perceived reduction in workload. Flight crew instructions for establishing the sequence were issued farther upstream, and late vectoring was reduced. In other words, controller decisions were less tactical and more strategic. This concept takes a small, initial step in separating the controller's strategic and tactical roles in ATM and distributing some of the latter to the flight crew of equipped aircraft. The positive research findings indicate that the basic idea of redistributing certain ATM functions has merit. This paper presents a more extensive application of this idea.

C. Crossing & passing

Another relevant example of using ASAS capability to reduce controller workload, and thereby potentially increase capacity by increasing the controller's availability, is the application of Crossing & Passing, investigated by MFF.[10] The objective, again, was to combine several controller actions distributed over time to a single clearance to be executed by the flight crew using ASAS technology and procedures. In a potential conflict situation, as shown in Figure 3 for example, the controller would be able to instruct the flight crew to "pass behind" the other aircraft to ensure a given separation. The procedure was studied in simulation, and critical problems were found leading to the dropping of this application from future research. In crossing situations, the closure speeds are much greater than those in merging or overtake situations, making controller monitoring a significant concern. The controllers were extremely uncomfortable retaining responsibility for separation while delegating the crossing maneuver to the flight crew. It is notable that the issue was not with the flight crew's ability, using ASAS support, to perform the operation. Reducing controller workload would require reliable monitoring automation for the controller or full trans-
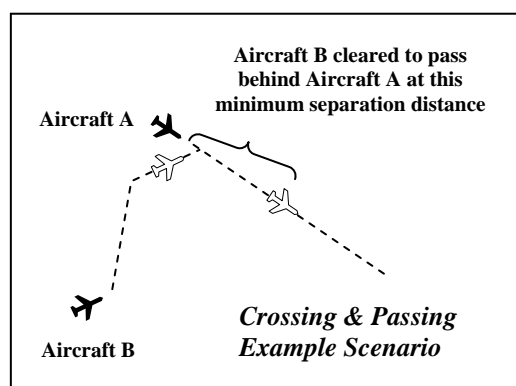

Figure 3. Crossing & Passing provides temporary delegation to the flight crew of a maneuver to ensure traffic separation.

fer of separation responsibility to the flight crew. However, repeatedly delegating temporary responsibility for near-term conflict management on a per-conflict basis may not be a workload reduction at all. This paper proposes operations in which this near-term conflict management is delegated by default to properly equipped aircraft.

III.   Integrating ASAS with 4D Trajectory Management

The hypothesis of this paper is that adding ASAS capability to aircraft equipped for 4DT operations increases the ability of that aircraft to contribute to meeting system-level ATM goals. By taking on ATM-related functions that would otherwise be performed by ground-based ATM systems, such an aircraft becomes less of a burden on the ground system than an aircraft without this ability. Expanding this idea to multiple aircraft, the distribution of ATM functions to a growing fleet of equipped aircraft thereby provides the foundation of a more scalable ATM system. 4D-ASAS may be among the most ATM-friendly equipage levels and therefore a candidate for the highest level of airspace access, provided a feasible implementation can be developed and safety can be adequately assured. This section provides a working definition of the 4D-ASAS capability level.

A. Long- and Near-term 4DT Air Traffic Management

What 4DT operations will look like and how it will be used in the NGATS is not yet fully determined. However, one should consider two time domains for 4DT operations that have reasonably distinct ATM objectives and requirements. The time domains are described here, relative to each flight, as long term and near term.

Long-term 4DT operations would generally span the majority of the flight, and its relevance to ATM is in predicting and managing the impact of this particular flight on the overall air traffic system, i.e. airspace loading and resource demand. It would involve managing departure and arrival times, and it would require knowledge of the approximate flight path for predicting sector loads and airspace complexity. However, neither highly accurate ground knowledge nor airborne adherence to the specific trajectory is as important here as is awareness of certain key attributes that must be known for managing the limited resources of the NAS. For example, as shown in Figure 4, it may be sufficient to know that, for weather avoidance, an aircraft plans to fly through a given sequence of sectors on a particular schedule in order to determine whether additional staffing is needed for those sectors or

Figure 4. Long-term 4DT management considers key TFM-related attributes such as airspace sector loading and arrival times.

whether to dynamically redefine the boundaries to accommodate additional demand. Highly accurate knowledge or tight conformance to a rigid 4D flight path is less relevant for these strategic decisions, as the decisions will likely be the same regardless of local flight path variations. The relevance of this point is that it allows a distinction between long-term and near-term 4DT operations, which have different objectives and requirements.
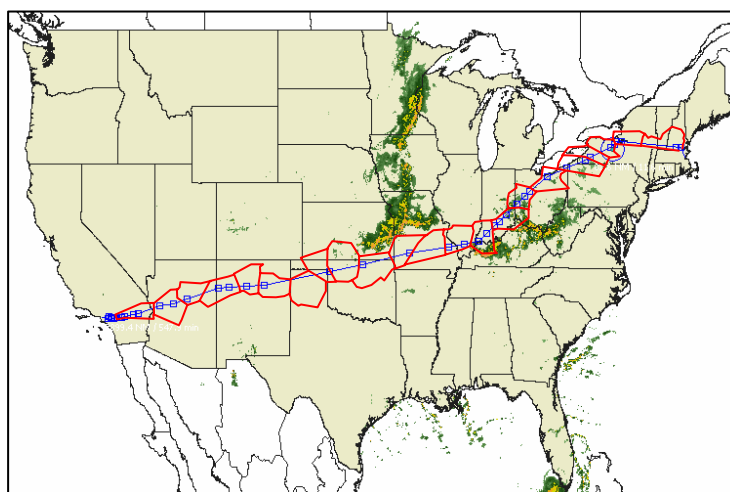
Near-term 4DT operations would cover the next short period when tactical decisions regarding the flight may be necessary, say within about 20 to 40 minutes. Tactical decisions resulting in flight path modification may be needed to resolve a local traffic conflict, for local weather avoidance, to make lift or drag configuration changes while in descent, or to accommodate other short-duration deviations, but they would not involve a change in strategic goals from the perspective of long-term 4DT operations. For example as shown in Figure 5, an aircraft's long-term trajectory may have the aircraft flying through a particular set of sectors containing some scattered convective weather cells. The flight crew may determine that a local deviation is necessary to avoid passing through an impending cell. The near-term trajectory will be modified to circumnavigate the hazard, but the sector traffic loads (current and downstream sectors) and estimated arrival time to the destination would be essentially unchanged. In this way the impact on long-term 4DT operations is negligible.

Making a distinction between long-term and near-term 4DT management is important because it can provide a degree of flexibility that is critical to managing flights within the dynamic environment of air traffic operations. It supports the notion stated earlier of decomposing ATM into a set of functions that are distributed to the most appropriate party. The flight crew may arguably be in the best position to determine the need for and appropriate implementation of local modifications to the trajectory, i.e. near-term 4DT management, given the dedicated attention the flight crew can give the situation and the personal observation of the local environment. Similarly, the ground side may be best suited for long-term issues that impact the total demand placed on limited NAS resources. As will be later discussed in the operational model, an aircraft with 4D-ASAS capability can actually add value to ATM in both time domains.
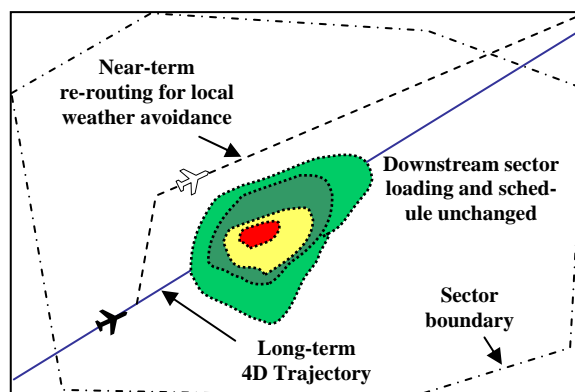

Figure 5. Re-routing of the near-term 4DT can be performed without disruption to the TFM attributes of the long-term 4DT.

B. 4D-ASAS Capability Level, Defined

The following set of technologies would likely be necessary to enable the capabilities envisioned for 4D-ASAS equipped aircraft. As will be discussed later, researchers at NASA Langley Research Center have developed a prototype software simulation for research purposes that approximately models this equipage level.

1. RNAV

Area Navigation capability allows aircraft to navigate relative to a route of custom-defined waypoints and not be limited to fixed route structures. This level of flexibility will be critical for 4D-ASAS aircraft to resolve certain problems within the dynamic airspace and traffic environment.

2. RTA

A capability to meet a Required Time of Arrival could be considered as one component of time management in 4DT operations. The implicit requirement is the ability to adjust speed and path as necessary (within aircraft operating limitations) to conform to some waypoint schedule constraint defined by an external source for TFM purposes. These waypoint constraints, typically specified as crossing times at a metering fix, are established as an ATM tool for creating a desired sequence among multiple arriving flights and establishing a traffic flow rate that matches the capacity of the limited resource. The RTA-meeting capability may be partially satisfied by speed adjustments enacted through a Flight Management System (FMS). However, some degree of path adjustment using the RNAV capability will probably also be necessary to accommodate short-notice or moderately sized RTA adjustments. Such adjustments by the ground-based scheduler will be a normal occurrence, given the variability of airspace operations and ground efforts to maximize use of resources. Although some current FMS systems have limited RTA-based speed management capability, no fielded systems as yet can determine RNAV path stretches to absorb a specified delay.

3. RNP

Airspace procedures use Required Navigation Performance to optimize operations in more highly constrained airspace. RNP requires aircraft that are following these procedures to adhere to a 3D path within a specified tolerance. The opportunities for using RNP to improve efficient and safe use of airspace are many. Tighter-than-normal tolerances can be used, for example, to enable approaches to terrain-impacted airports. RNP may also have future application in reducing traffic separation standards, allowing an increase in capacity of high-demand airspace. For 4D-ASAS aircraft to have access to this airspace, it must be capable of adhering to the local RNP criteria, which may be quite strict. Even when flying an airborne-derived 4DT (i.e. specified by the aircraft, not a ground system), RNP is important. Aircraft will broadcast its current RNP level in real time, and it will tell other aircraft and ground systems that their predictions can rely on this level of ownship adherence to the broadcast trajectory.

4. ADS-B (out and in)

Automatic Dependent Surveillance Broadcast is a distributed technology that transmits position and intent data from broadcasting aircraft (i.e. "ADS-B Out"). The technology is also capable of receiving this data onboard aircraft (i.e. "ADS-B In"), and both the transmit and receive capabilities are essential for 4D-ASAS aircraft. By re-

ceiving a complete set of surveillance data, the aircraft systems can now perform ATM-related functions that require knowledge of the local traffic picture.

5. *ASAS*

Once the proper surveillance data is brought onboard, many possible applications for 4D-ASAS aircraft can be pursued. The ones with the most significant ATM value have at least one important common denominator: *the flight crew can now precisely maneuver their aircraft relative to other aircraft, without requiring detailed instruction from ground systems.* Two major categories of this ASAS capability are described next. The first enables aircraft to restore, maintain, or increase the prediction of adequate separation from other traffic, an important ATM function for safety and effective use of airspace. The second enables aircraft to draw closer together in a controlled fashion, an important ATM function for sharing limited resources such as a runway. The true resource value of 4D-ASAS capability to ATM is embedded in the transfer of these functions to the 4D-ASAS aircraft by default, so that the tactical details can be managed locally and the ground systems can stay focused on managing the strategic situation.

a. *Airborne Conflict Management*

The ASAS capability for Airborne Conflict Management (ACM) allows a 4D-ASAS aircraft to make local adjustments to its 4DT to ensure at least the minimum separation standard is maintained from all other aircraft. ACM capability is applicable both to detecting and resolving conflicts predicted along the current 4DT and to generating modifications to the 4DT for any reason (e.g., to clear an impending convective weather cell), in which prevention of new conflicts is required. In the NASA Langley R&D implementation of ACM,[11] this capability uses knowledge of the own aircraft's state, current commanded and planned 4D trajectories, and any provisional (i.e. trial plan) trajectories to be explored, as well as the state and broadcast intent (i.e. the near-term 4D trajectories) of local traffic. (It should be noted that full origin-to-destination 4D trajectories are not necessary to manage local traffic separation issues.) Taking into account aircraft performance limitations and the local airspace environment (e.g., winds, airspace restrictions), conflict-free RNAV trajectories are calculated for flight crew review, selection, and execution.

b. *Airborne Precision Spacing*

The ASAS capability for Airborne Precision Spacing (APS) allows a 4D-ASAS aircraft to manage the merging and longitudinal compression with a lead aircraft as both progress toward a common point, for example, the runway threshold. In the NASA Langley R&D implementation of APS,[12] this capability uses knowledge of both aircraft's routes (which may be different routes) toward the common point, ADS-B surveillance of the lead aircraft position and speed, a published reference descent speed profile, and knowledge of the own aircraft's configuration speed limits. An onboard automation system uses this real-time information to calculate airspeed changes to be followed by the flight crew or auto-throttle system. The speed changes ensure that the own aircraft follows the lead aircraft across the common point (e.g. runway threshold) at precisely the time or distance interval desired by the controller. The Langley prototype capabilities for both en-route ACM and terminal-arrival APS are described in greater detail in Section V.

6. *Integrated 4D-ASAS Capability*

Integrating the above-listed capabilities provides a strong airborne platform supporting ATM. Several examples where integration is useful can be cited. For instance, pairing ASAS and RNAV capabilities permit much flexibility in managing diverse traffic situations where airspace is relatively unconstrained for maneuvering. In more highly constrained environments, RNP can play an important role in keeping ASAS-derived maneuvers to tight tolerances and allowing potential reduction in separation standards for increased airspace capacity. RTA-meeting capability can be treated as an operational constraint by ASAS when exploring possible trajectory modifications, thereby simultaneously meeting separation and flow management goals. In addition, pairing RTA, RNAV, and ASAS permits conflict-free path stretching to accommodate changing TFM requirements (e.g. delay absorption). ADS-B enables ground-based and airborne receiving audiences to be kept informed of the current 4DT and RNP tolerances. These examples illustrate how an aircraft equipped with the integrated 4D-ASAS capability can perform functions of strategic relevance to ATM that aircraft without ASAS cannot perform. 4D-ASAS may therefore be considered perhaps the highest level of equipage for airspace operations and may therefore be capable of facilitating the most complex ATM situations. The next section proposes one possible model for how 4D-ASAS capability can support ATM.

IV.   A Potential Model for 4D-ASAS Operations

The capabilities of 4D-ASAS equipage were shown in the previous section to be highly relevant to ATM. However, the actual *value* to ATM will be dependent on how aircraft and ground systems can use this capability to a strategic advantage. To illustrate the potential, a model of operations is offered that uses 4D-ASAS airborne capability integrated with ground-based TFM. As described earlier, a variety of opportunities exist for ASAS applications in an ATM environment, such as aiding visual acquisition. The model put forth here focuses on the more far reaching value 4D-ASAS capabilities might be able to give ATM. An illustration of a typical flight will be used, and the assumption is made that the flight will traverse complex, high-demand airspace and will arrive to a capacity-constrained airport. Note that 4D-ASAS operations would not be restricted to these complex environments or to airlines but would be available to any airspace user that chooses to equip, including those in military, private and corporate general aviation in essentially all regions of airspace.

A. Pre-Departure

Prior to departure, the nominal flight path and schedule (i.e. the initial 4DT) are generated from a flight plan filed by the operator. The flight plan takes into account operator schedule needs and cost optimization criteria, resulting in a proposed 4D route with arrival time. The route would typically be a wind-optimized great circle route, but could also conform to other airspace design features such as high-capacity airways. TFM authorities review the flight plan against predicted airspace loading and arrival /departure airport demand, and they update their system-wide predictions for resource utilization. Given enough notice (and flight plans from other aircraft), the staffing requirements and airspace sectorization definitions are updated to accommodate the additional demand, although as will be shown, 4D-ASAS aircraft place minimal burden on ground systems. Amendments to 4D-ASAS flight plans by TFM authorities are generally not needed, given the ATM-supporting capabilities the aircraft will put to use in flight. An exception may be an amendment to initially de-conflict 4D trajectories between aircraft for the initial departure phase. Full trajectory de-confliction is not attempted due to the many variables affecting long-term trajectory prediction accuracy, such as individual aircraft performance variations, complex atmospheric conditions and change rates, and unanticipated departure delays.

B. Departure and Climb-Out

The 4D-ASAS aircraft is given priority in departure because its TFM-related impact downstream has already been accounted for in the 4DT derived from the flight plan, both en-route and at the scheduled arrival time. After departure, the 4D-ASAS aircraft climbs out in RNP conformance with the initially de-conflicted RNAV trajectory. As the aircraft proceeds en route, near-term and long-term 4DT operational procedures are followed, as described next.

C. En-route Near-Term 4DT Operations

Near-term 4DT operations for the 4D-ASAS aircraft begins with regular, automatic exchange of surveillance data. Broadcast information includes the near-term 4DT (i.e. the next few flight segments) and the current RNP conformance level. Because traffic separation is of primary importance to ATM in the near-term domain, other aircraft and ground systems rely on this broadcast information to build and maintain shared situation awareness.

The 4D-ASAS aircraft uses surveillance data received from other aircraft and airspace hazard information for three important ATM contributions related to ACM: (1) conflict detection and resolution; (2) conflict-free maneuvering; and (3) risk exposure assessment and mitigation. Each can require near-term deviations from the current 4DT to meet local constraints, and yet a principal goal for all three is to maintain the basic attributes of the long-term 4DT such that ground-based TFM is not affected. These attributes include the general airspace to be traversed (e.g. sectors) and the estimated time of arrival.

Conflict detection and resolution

The current 4DT is continually compared to those of nearby traffic in search of current or potential conflicts (i.e. prediction of separation loss). The conflict scanning is performed by the ASAS automation's ACM function. The flight crew has access to the traffic picture and is appropriately alerted to conflict situations in adequate time to take action. The ASAS automation provides conflict resolution alternatives to the flight crew, usually in the form of modified (either lateral or vertical) 4D trajectories which reconnect to the original long-term 4DT and that can be fully implemented through the FMS. The example scenario in Figure 6 indicates a resolution maneuver that also avoids a weather hazard. In some situations, tactical resolution maneuvers (i.e. akin to ATC vectors) are provided instead, either because the flight crew requested it from ASAS for flight-practical reasons (e.g., the cur-

rent weather environment precludes FMS navigation) or because time pressure requires faster action. In such cases, the flight crew would determine the appropriate time and maneuvers (using ASAS) to return on course. Any conflict resolution maneuver results in a change to the near-term 4DT, and so the new trajectory is immediately (and automatically) broadcast so that nearby aircraft and ground systems can update their models of the local traffic situation. In the case of tactical maneuvering, the updated trajectory may not reconnect if, for example, the aircraft is on a vector. Even though the broadcast trajectory is open ended, the 4D-ASAS aircraft is committing to conform to the broadcast 4DT (e.g. fly that heading at that airspeed) until such time that a conflict-free reconnect maneuver is properly performed and announced.

Figure 6. Near-term changes to the 4DT by 4D-ASAS aircraft are immediately broadcast to maintain shared awareness of intent.

Conflict-free maneuvering

The 4D-ASAS flight crew may revise the near-term 4DT for a variety of tactical reasons, using ASAS capabilities supporting conflict-free maneuvering, without coordinating with ground authorities. Reasons for maneuvering may include avoiding local hazardous weather cells, changing to a less turbulent flight level, or reducing general risk exposure (as described below). To accomplish this, the crew uses the ASAS automation as others would use ATC, to ensure the proposed maneuver does not unacceptably increase the risk of conflict or force near-term maneuvers on other aircraft. Again, the new near-term 4DT is immediately broadcast upon execution to maintain the shared situation awareness with other airborne and ground systems.

Risk exposure assessment and mitigation

Of equal importance to the first two ATM contributions is a third one that addresses situation complexity and stability, i.e. the continual near-term assessment of whether continued flight along the current 4DT will expose the aircraft to a degraded situation with unacceptably reduced maneuvering flexibility. Maneuver flexibility is the most important ATM resource for accommodating unexpected near-term events, and both 4D-ASAS flight crews and ground-based controllers endeavor to preserve this resource for their respective aircraft to the extent possible. ASAS automation assesses risk exposure by probing variations of the current 4DT in search of conflict- and hazard-free maneuvering degrees of freedom. Even though the current trajectory may be conflict free, the surrounding airspace may be too constrained to permit conflict-free maneuvering should the need to maneuver arise. In this situation, the risk exposure may be too high, and the best course of action may be to preempt the situation with a trajectory replan. The extent of the replan determines whether its effect is only near term, or whether long-term 4DT operations must be addressed. This 4D-ASAS function is therefore the bridge between near-term and long-term 4DT operations.

An example scenario is shown in Figure 7. The aircraft labeled "ownship" is approaching an airspace region constrained by convective weather and local traffic. In this case, the convective weather closed in faster than forecast, resulting in traffic bottlenecks through the gaps. The ASAS system continually scans the traffic and weather situation along and nearby the current 4DT, looking for maneuvering constraints. If the risk of proceeding is beyond a predetermined acceptability threshold, the 4D-ASAS aircraft scans alternative
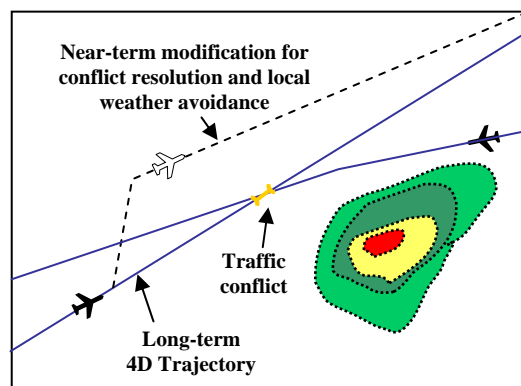

ASAS determines maneuver flexibility prior to entering constrained area

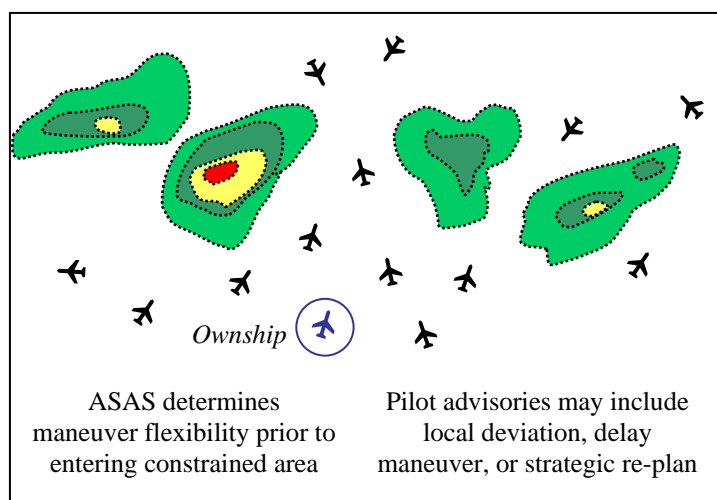Pilot advisories may include local deviation, delay maneuver, or strategic re-plan

Figure 7. 4D-ASAS aircraft continually assesses near-term maneuvering flexibility and takes preemptive action to preserve options. If performed by many 4D-ASAS aircraft, airspace complexity management is possible.

passages through the weather. Provided one is found that preserves the long-term 4DT attributes (i.e. sectors traversed and schedule), the maneuver remains within the purview of near-term 4DT operations. The alternative situation will be described below.

In each of these three cases, near-term 4DT management is delegated by default to the 4D-ASAS flight crew. This delegation means that the flight crew, using reliable ASAS automation, is responsible for any near-term deviations to resolve conflicts or avoid hazards, and that they will preserve the principal attributes of the long-term 4DT.

D. En-route Long-Term 4DT Operations

For long-term 4DT operations, the 4D-ASAS aircraft has two functions. First and foremost, the aircraft conforms to the 4DT using its RNAV, RNP, and RTA-meeting capabilities. The action here is simply for the 4D-ASAS aircraft to be where it is expected so that system-level TFM predictions are realized.

Second, the aircraft determines whether a change to the long-term 4DT is required and coordinates appropriately with ground-based TFM authorities. The example scenario in the previous section, shown in Figure 7, provides an instance where such a change may be requested. The situation might have developed differently such that continuation towards the weather would result in unacceptable exposure to risk. Since a large diversion around the weather would take the flight into unanticipated sectors and probably result in significant disruption to the flight schedule (e.g. the arrival RTA), the 4D-ASAS aircraft flight crew responsibilities regarding long-term 4DT management now come into play. The flight crew uses the 4D-ASAS capabilities to plan a new route that remains clear of the weather and provides adequate initial traffic separation (i.e. also a near-term 4DT ATM function). The route is coordinated with ground-based TFM authorities to update predictions of sector loads and the arrival schedule. A new arrival slot is generated for the aircraft, and ground systems are updated with the new 4DT. The 4D-ASAS aircraft then proceeds to conform to the new 4DT using its RNAV, RNP, and RTA-meeting capabilities.

E. Terminal Arrival

As the 4D-ASAS aircraft prepares for arrival and begins descent, ground systems continue the dynamic tasks of runway load balancing, establishing runway assignments for each flight, and updating the expected arrival sequence for each runway. Ground systems communicate to the 4D-ASAS aircraft the RNAV arrival path to be tracked to the runway, the lead aircraft to follow, and the threshold-crossing-time interval to be achieved behind the lead. This interval is customized for each aircraft pair to account for aircraft wake class, environmental conditions, and surface traffic, with the objective of maximizing runway throughput. The lead aircraft may be arriving from a different direction, as indicated in the example in Figure 8, and yet the two aircraft will eventually merge prior to the final approach segment. Using its APS capability, the 4D-ASAS aircraft provides a valuable ATM service by managing all tactical speed changes necessary during the arrival to gradually null out any spacing discrepancy by the time the final approach is commenced. The 4D-ASAS aircraft also performs lateral off-path maneuvering (within approved limits) to absorb or create larger gaps as needed by ground controllers for accommodating changes to the runway usage plan. The APS automation smoothly transitions the 4D-ASAS aircraft to its final approach speed, and the flight is completed.
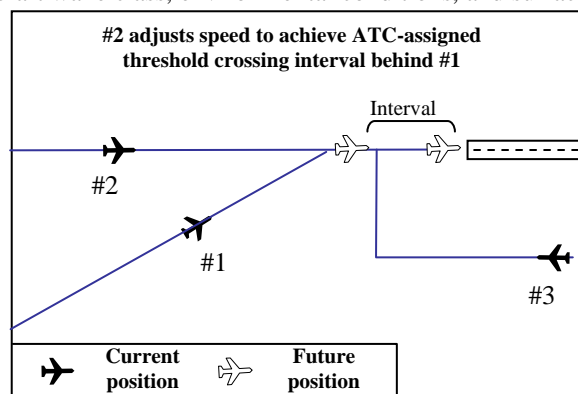

Figure 8. 4D-ASAS aircraft support the ATC-planned arrival flow by performing any tactical speed adjustments necessary to achieve their assigned pair-specific crossing interval.

This illustration of a typical flight shows how the capabilities provided by 4D-ASAS enable the aircraft to be a truly effective ATM resource within the model of 4DT operations. The effectiveness is borne in the ability to manage tactical issues at shorter time horizons while maintaining conformance to the longer-term strategic ATM requirements established for that aircraft that are critical to TFM. For example, the ACM capability can be developed to consider the RTA as an operational constraint to any 4DT modifications. In the case of a traffic conflict, the automation can be designed to seek out a maneuver that restores predicted separation to acceptable values and yet still allows the RTA (i.e. the TFM parameter of most interest to the ground scheduler) to be met. As another example, the APS automation can be designed to consider the flap deployment schedule (different for each aircraft type) as an operational constraint to the spacing procedure. Local ad-

justments in the timing of speed changes will be made, while the runway throughput goal of interest to TFM is maintained. These examples show that aircraft with integrated 4D-ASAS capability can work effectively together with traffic flow managers and can off-load ground systems in situations where high operational complexity necessitates elevating the ground-based human decision maker to work at a higher level of abstraction.

V.   NASA Research and Development of 4D-ASAS Capabilities

Researchers at NASA Langley Research Center have been developing and studying advanced ATM concepts that incorporate 4D-ASAS capabilities similar to those described above. To support the investigations, software prototypes of the decision support technology were developed. For the en-route and terminal arrival operational domains, the sections below summarize the principal airborne functional capabilities developed and studied that are relevant to the 4D-ASAS operations proposed in this paper. The research and development (R&D) presented here was performed to assess feasibility of the Distributed Air-Ground Traffic Management (DAG-TM) Concept Elements 5 and 11.[13,14]

A. En-Route Operations

Langley researchers have developed, and continue to refine, a software-prototype airborne decision-support tool called the Autonomous Operations Planner (AOP), which provides ASAS functionality applicable to en-route and terminal-transition operations.[15] The AOP is integrated into the avionics architecture of an advanced Boeing-style glass-cockpit aircraft simulation. This aircraft simulation also has an RTA-capable FMS, an auto-flight / auto-throttle system, a Mode-S ADS-B transceiver, and realistic flight displays and controls for piloted operation. In addition, the avionics architecture through which AOP is integrated is an accurate model of an ARINC 429 Avionics Bus.[16] Therefore, the aircraft equipage closely represents the integrated capabilities required of a 4D-ASAS aircraft, as described earlier.

AOP was designed to support flight crew decision-making in autonomous aircraft operations, a concept in which the flight crew retains responsibility for traffic separation, restricted and hazardous airspace avoidance, and TFM arrival-time conformance in a mixed-equipage en-route and initial-descent environment.[11] The principal AOP functions include conflict detection and resolution, conflict assessment of provisional maneuvers prior to execution, and path stretching for arrival delay absorption. Although originally developed for a different conceptual application, each of these functions is pertinent to the 4D-ASAS operations described in this paper. Planned for AOP but not yet developed is the functionality of risk exposure assessment, described earlier, which will predict degradation of near-term maneuvering degrees of freedom in complex environments and alert the crew to take alternate action. An example of how typical conflict information is presented by AOP to the flight crew is shown in Figure 9.

The airborne conflict management capabilities of AOP use traffic state and intent information received over ADS-B, as well as multiple levels of ownship trajectory prediction. AOP's integration with the avionic architecture enables AOP knowledge of the "command" trajectory, i.e. the real-time 4DT implemented in the auto-flight system, including limits and constraints imposed by the FMS and Mode Control Panel settings. The command trajectory is the most accurate near-term 4DT available, and the aircraft will fly this trajectory

Figure 9. Conflict alerting, resolution, and prevention information from AOP are displayed to the flight crew.

until redirected by the flight crew. It is shared with nearby aircraft and ground systems over ADS-B to promote shared situation awareness. AOP developers are currently in the early stages of implementing the ability to consider RNP in conflict management. The initial capability applies buffers to trajectory predictions based on trajectory segment type. For example, greater buffers are applied to turns and top-of-descent than to straight, level segments. Eventually, AOP will be able to customize each trajectory uncertainty buffer as a function of RNP received from traffic aircraft over ADS-B.
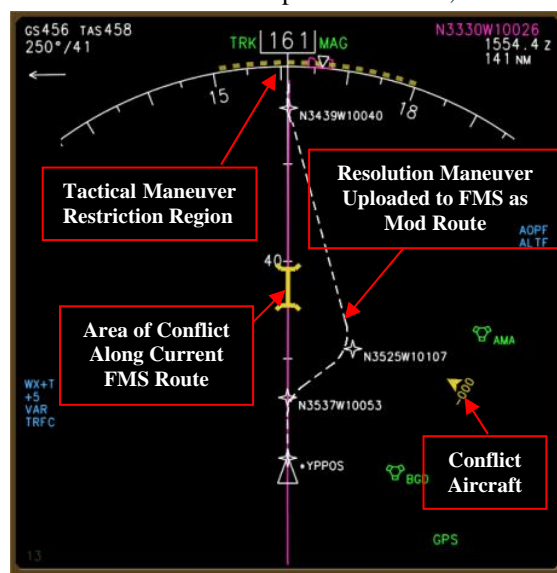
A design goal for AOP was to support multiple flight-mode configurations. Real-world operational considerations make impractical a requirement for aircraft to be flown only in FMS-coupled flight, in which all guidance commands to the auto-flight system come from the 4D FMS trajectory. Tactical situations will always occur, even in future operations based on 4DT management, that require the flight crew to intervene with tactical maneuvers, and it was intended that AOP services not be disrupted at these times. Therefore, AOP adapts its conflict management functions (i.e. detection, resolution, and prevention) to the current flight mode (e.g., heading hold, altitude hold). In addition, it supports transitions between modes, thereby alerting the flight crew to conflicts that would be created if the flight mode were changed.

The design features described above illustrate the extent to which AOP was designed to address the feasibility of operational implementation of autonomous aircraft operations. These enabling capabilities closely match those needed for 4D-ASAS operations. AOP was tested by airline pilots under a variety of simulated scenarios involving near- and long-term 4DT operational challenges.[17,18,19] These challenges involved operational constraints such as RTAs, scripted and unscripted conflicts of varying geometry (e.g., lateral, vertical, converging, opposing, intent blunders), pop-up situations, airspace hazards, and mixed equipage. Each study has assisted in improving AOP functionality and flight crew procedures, and has provided initial validation of the capabilities in airborne separation and TFM conformance enabled by 4D-ASAS equipage.

B. Terminal Arrival Operations

The nature of terminal arrival operations is aircraft arriving from different directions merging together in a controlled, carefully spaced sequence in order to make maximum use of a limited resource, i.e. a common runway. As operational complexity of the terminal environment increases, ATM challenges compound. Among the challenges that must be accommodated are dynamic arrival scheduling, runway load balancing, wake vortex impacts, surface movement considerations, different aircraft descent and deceleration performance characteristics, and air-ground communications workload, to name but a few. A particular research focus at Langley has been the development of an airborne merging and spacing tool that capitalizes on an effective air-ground distribution of ATM functions defined in DAG-TM Concept Element 11. The airborne tool, called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR), is a 4D-ASAS capability that enables flight crews and controllers to achieve a precise runway threshold crossing interval (time or distance) between pairs of aircraft.[12] The capability can be applied to extended streams of arrivals to maximize productivity of a given runway. This productivity is accomplished by reducing arrival-time dispersion per aircraft, thereby increasing the number of usable landing (or departure) slots.

AMSTAR uses predefined RNAV routing for both the ownship and the assigned lead aircraft as a basis for performing its spacing functions. The routing may be different between the two aircraft but are assumed to merge prior to the final approach fix of a common runway. Aircraft external to this arrival stream are kept segregated by airspace design and the controller. In addition to the predefined RNAV arrival paths, a predefined profile for altitude and speed is established which AMSTAR uses as the reference profile for the ownship. Changes in speed to reduce or

increase the spacing relative to the lead aircraft are made relative to this reference profile. For operational acceptability and improved arrival-stream stability, AMSTAR limits speed excursions to ten percent of the current profile speed. If greater speed changes are calculated, an exceptional event has likely happened and speed control reverts to the controller.

The surveillance data source for AMSTAR is ADS-B. In the event that the lead aircraft is beyond ADS-B range when the controller issues the spacing clearance, AMSTAR will follow the reference profile until ADS-B messages are received and active spacing can begin. AMSTAR maintains a limited history of ADS-B data for the
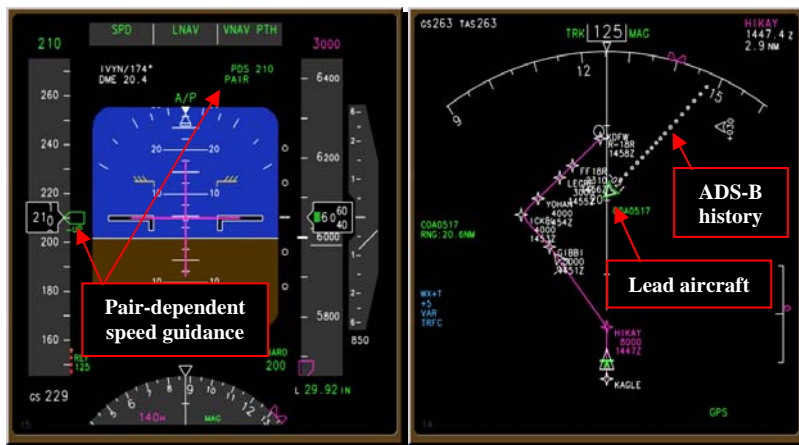

Figure 10. AMSTAR provides speed guidance to help the aircraft achieve the assigned threshold-crossing interval behind the lead aircraft.

lead aircraft and displays this history to the flight crew to promote situation awareness, particularly valuable in merge situations. The history is also used by AMSTAR to provide speed guidance in the event of in-trail operations in which the controller vectors the lead aircraft off the RNAV path (e.g. weather avoidance, runway configuration change) and the trailing aircraft is expected to follow at an assigned time interval for an unknown duration.

In the nominal situation in which both aircraft remain on their RNAV paths, as shown in Figure 10, the AMSTAR tool calculates the estimated time of arrival at the target location (e.g. runway threshold) for both the lead and own aircraft, incorporating real-time observations of the lead aircraft's varying speed (because it is also performing spacing on its lead aircraft), and it determines airspeed targets for the host aircraft that will gradually null out any time or distance error predicted for the target location prior to commencing the final approach. The airspeed targets are presented to the flight crew but can also be supplied directly to the auto-throttle system, if available. AMSTAR keeps track of aircraft flap configuration and will not command speeds outside of safe operating limits.

The design of AMSTAR is consistent with the 4D-ASAS capability requirements proposed in this paper for 4DT operations in the terminal arrival environment. The capability would also be applicable to other ATM applications that involve achieving, maintaining, or reducing in a controlled manner the spacing between aircraft. AMSTAR functionality and performance for merging and spacing has undergone substantial testing and analysis through batch and piloted simulations.[20,21,22] Batch simulations have analyzed the system performance of 100-aircraft arrival streams with variations in aircraft types, merge sequence, entry time precision, ADS-B reception range, wind prediction accuracy, knowledge of lead-aircraft final approach speed, and descent profile including continuous descent approaches. Piloted simulations addressed flight crew procedures and the adaptability of airborne precision spacing to different RNAV route geometries (i.e. airports). In addition to the simulations, a flight evaluation was performed at the Chicago O'Hare airport to evaluate in-trail capabilities in a real-world environment.[23] As was the case for AOP, these studies have assisted in improving AMSTAR functionality, flight crew procedures, and the resulting system performance, and they have provided initial validation of the precision spacing capabilities enabled by 4D-ASAS equipage.

VI.   Addressing ATM Challenges with 4D-ASAS

The JPDO faces several extraordinary challenges in designing a viable ATM system for the future. Incorporating the 4D-ASAS equipage level may have positive impact in several areas.

A. Reducing Ground Infrastructure Costs

Allowing the aircraft to carry onboard the infrastructure for certain ATM functions partially relieves the need for equivalent infrastructure on the ground. Potential ground-based infrastructure reduction includes surveillance equipment (i.e. radar) with the advent of ADS-B, but may also include costly and complex automation systems for 4DT operations that are not yet designed. Of course, not all ground capability can be eliminated, since not all aircraft will be equipped for 4D-ASAS operations. However, the sophistication required of the ground automation can be reduced, because the complexity of the traffic environment will drive the level of sophistication of ground systems. Designing and building an automation system capable of full 4DT operations for all aircraft at all levels of traffic complexity may prove far more difficult and costly and take far longer than the time available, considering the traffic growth rate. Yet, with onboard ASAS off-loading the ground systems of some ATM functions, the ground automation sophistication may be significantly reduced. The primary reason this may be true is that by delegating near-term 4DT management to the aircraft, the remaining function of long-term 4DT management becomes greatly simplified. It becomes primarily a task of dynamic load prediction and scheduling of limited-capacity resources. In contrast to full 4DT operations, it should be much more feasible and affordable to safely automate the load prediction and scheduling tasks, with oversight and strategic decision making provided by TFM personnel.

Developing automation to support 4D-ASAS flight crews in near-term 4DT operations may in fact be far more feasible and affordable than a ground system with separation responsibility for all aircraft. Two principal reasons are simplicity and communications. The traffic problem faced by an aircraft-centric system (i.e. ASAS) is much simpler than the full traffic problem faced by the ground system. Only the objectives and constraints that impact the host aircraft must be reconciled, and provided that certain coordination rules are followed (e.g., right-of-way between aircraft), adverse interactions within the traffic population can be avoided. In addition, local peaks of complexity can be mitigated with a combination of distributed risk-exposure assessment, described earlier in Section IV, and TFM sequencing or scheduling. In the area of communications, if near-term 4DT decisions are collocated with the aircraft, the air-ground communications infrastructure can be significantly reduced. In addition to augmenting cost for

both airborne and ground systems, communication links inject latency and failure modes into the time domain of aircraft separation, which may adversely impact safety.

B. Building in Security and Safety

Two key desired characteristics of the NGATS are that security and safety be built in from the start and that they not be inhibitors of growth. A major liability of the current system in both security and safety is the centralization of key functions within relatively concentrated ground facilities. Three key parts of the safety-critical infrastructure of the ATM system are (1) facilities housing air traffic controllers, (2) radar site installations, and (3) communication towers. Redundancies are built in, but switching to the redundant systems often provides significant periods of service disruption. Operations during these service disruptions are considered highly off-nominal, and the effect on traffic flows can be substantial and enduring. Significant disruptions have occurred in recent past.[24] During such disruptions, safety is maintained by the training, experience, and calm professionalism of the air traffic service personnel and the flight crews. However, the limits of maintaining readiness for this situation can be a substantial inhibitor of growth.

Securing the ATM system from inadvertent disruption, or from deliberate attack, will be challenging and costly wherever infrastructure is centralized and vulnerable. Any one disruptive event is amplified by the number of aircraft that depend on the affected system. Herein resides the advantage of distributed or networked systems. A failure of one node does not cripple large portions of the system. Of the three components of safety-critical infrastructure listed above, all three are positively impacted by 4D-ASAS aircraft. In the first instance, an ASAS failure on one aircraft is not amplified as an ATM loss for all aircraft in the airspace. Rather, it remains a single failure which can be managed similar to lost-communication procedures today. In the second instance, surveillance is fully distributed using ADS-B, and a single failure is contained to that aircraft. In the third instance, the criticality of air-ground communications is greatly diminished by collocating decision-making with maneuver execution on the flight deck. All three cases illustrate how the vulnerability of the ATM system is significantly reduced by distributing the critical infrastructure and decision-making authority.

Naturally, some will consider giving the flight crew the authority to maneuver at will to be a reduction in security and safety. Safety is a technical issue that can be addressed through methodical system design, thorough testing, and critical analysis. A safe implementation can be accomplished in a distributed system if safety is maintained as a principal design goal. Security is more an issue of intent knowledge and direct aircraft control. The issue of direct aircraft control is unchanged from the current system, since the actual aircraft trajectory is ultimately controlled from the flight deck. Regarding intent knowledge, 4D-ASAS aircraft provide intent awareness to security officials by filing 4DT flight plans, broadcasting real-time intent automatically from the auto-flight system, and conforming to RNP tolerances. Ground systems can easily monitor aircraft progress toward their filed destination and can alert security personnel to deviations as soon as they happen so that the flight crew can be contacted. In addition, these safety and security characteristics are derived through airborne systems, and therefore do not inherently inhibit growth, as can be the case with fixed ground systems

C. Scaling to Traffic Demand

Given the shear enormity of devising and implementing the transformational changes in air transportation currently envisioned by the JPDO, an overarching goal beyond all else except affordability must be ensuring the new system can safely accommodate traffic growth for the foreseeable future and will not have to be reinvented again any time soon. The common term is "scalability," and it implies, among other things, an ATM system that self-adapts to changing demand without the need to continually add costly ground infrastructure as traffic demand grows. The 4D-ASAS equipage level directly supports scalability, in that the aircraft literally flies the infrastructure into the airspace when it is needed, and furthermore it flies it out when the need for the capability disappears. This second point is also an important affordability argument, because it enables the ATM system to scale down at times of reduced demand, something a fixed ground infrastructure cannot do. The reduced demand may occur by time of day, by region, or by the national or global economic cycle. In order to gain the scalability benefit of 4D-ASAS aircraft, they must be permitted access to the airspace in highest demand, and probably given the highest priority within this airspace. Without this, operators will have little incentive to equip for 4D-ASAS operations, and this valuable ATM resource will not find its way into the airspace in which it is most needed.

VII. Conclusion

This paper has described how an aircraft equipped with ASAS and 4DT operational capabilities could have significant, potentially transforming ATM value. The future air traffic environment is envisioned by the JPDO to be characterized in part by net-enabled information access, performance-based services, and aircraft trajectory-based operations. These assumptions lay the groundwork for redistributing ATM functions based not on information location, but rather on performance achievement capability. Near-term ASAS applications under exploration were highlighted to illuminate key considerations in effectively distributing ATM functions between controllers and flight crews.

A new aircraft equipage level was then proposed in which ASAS and 4DT operational capabilities are integrated to enable a more valuable and effective role for equipped aircraft in supporting ATM. A hypothetical model of operations for "4D-ASAS" aircraft was presented to illustrate the potential interaction such aircraft might have with the dynamic airspace environment and with ground-based TFM, with a purposeful distinction made between the aircraft's role in near- and long-term 4DT management. A summary of NASA's R&D of the proposed aircraft equipage for en-route and terminal-arrival operations was presented.

Finally, the role the 4D-ASAS equipage level might play in addressing three key implementation challenges faced by those defining the Next Generation Air Transportation System was discussed. First, it was shown how ground infrastructure costs may be reduced by distributing surveillance infrastructure and certain ATM automation functions, such as near-term 4DT management, to the aircraft. It was argued that the remaining ground automation requirements would be greatly simplified, thereby enabling reductions in both cost and implementation risk. Next discussed were the security and safety benefits of eliminating single-point vulnerabilities in ATM decision making, surveillance infrastructure, and communication links inherent in a highly ground-centric ATM system. It was then shown that achieving ATM scalability to significant trends in traffic demand can be enabled by equipping aircraft to literally fly the ATM capabilities into high-demand environments only where and when they are most needed.

More and more, the aviation community is giving greater credence to the transformational impact ASAS capabilities could have on airspace operations. The benefit to system-wide ATM will depend on the context in which these capabilities are applied. This paper has shown that integrating ASAS capabilities with those required for 4DT operations results in a powerful distributed resource for both local- and system-level TFM. Because of its relevance to ATM and its potential to help address key ATM challenges, the integrated 4D-ASAS equipage level warrants further consideration in the development of an agile air traffic system.

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